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Evaluation of the LINCOM wind field reconstruction method with simulations and full-scale measurements

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Abstract. The LINCOM method is a set of linearised flow equations that enables the reconstruction of a 3D wind field from a large set of non-parallel radial wind speed measurements. An evaluation of the model is performed with both simulated and full-scale boundary layer wind field measurements. The model is first tested on deterministic wind fields to evaluate its performance under simple conditions. Afterwards, line-of-sight measurements are extracted from a virtual SpinnerLidar placed in an LES wind field and then the LINCOM method is applied and compared to it. Finally, the methodology is experimentally evaluated with lidar measurements from the IRPWIND joint experiment SCANFLOW campaign, where SpinnerLidar line-of-sight inflow measurements from the nacelle of a test turbine were used to reconstruct 3D wind fields. These reconstructed wind fields are then compared with simultaneously measured independent full-scale 3D short-range WindScanner data. It was seen that the LINCOM model is able to accurately reconstruct the deterministic wind fields. For the analysis with the LES wind fields, the LINCOM model is able to obtain an R^2 coefficient of 0.72 with no significant correlation found for the v - and w -components. The cosine de-projection of the line-of-sight speeds onto the main direction yields $R^2 = 0.834$. For the full field measurements, the LINCOM model was able to predict the longitudinal component with a low standard error, but the v - and w -components deviate significantly. The results suggest the suitability of the model to reconstruct only the mean characteristics of 3D fields under low turbulent conditions, and give a reasonable estimate of the fluctuations of the u -component.

1. Introduction

For the purpose of real time control of wind turbines, it is important to have dynamic wind field information of the incoming flow fields. The advancements in optical technology in the last two decades made lidars viable devices for deployment on wind turbines to measure the fluctuations in wind fields [1]. Information from a turbine-mounted lidar can be processed into mean parameters to form a representation of the wind field [2] and this information can be used as an input for controllers for the purpose of optimising power production and reducing the turbine loads [3]. However, a single turbine-mounted lidar is incapable of measuring all three wind components at its measurement points as only the wind speed along the line-of-sight of the laser beam is recorded. This is commonly referred to as the cyclops' dilemma and is an inherent limitation of wind lidars. Combining lidar line-of-sight (v_{LOS}) measurements with a computationally inexpensive linearised flow solver like LINCOM [4] has been proposed as one



way of bypassing this problem by estimating a set of three wind components that are consistent with the line-of-sight measurements.

The LINCOM model is a linearised flow solver that satisfies the conservation of mass and momentum equations. It uses the lidar line-of-sight measurements as a boundary condition, yielding a 3D wind field representation on a vertically aligned 2D grid. Since it solves the equations in the frequency domain, it is not computationally expensive. Further details about the LINCOM algorithm can be read in [5]. An earlier application demonstrated the calculation of the spatial wind speed variations in case of a stationary, non-rotating inflow [4].

In this paper, the evaluation of the LINCOM wind field reconstruction model is performed for various simulated and experimental data. The model is tested for simulated deterministic wind fields, lidar measurements based on a LES wind field and finally with free-field measurements.

2. Method and Validation

The LINCOM Solver

The LINCOM model is based on solving the linearised mass and momentum equations on a 2D grid in the Fourier space. In this model, the x -axis points into the wind, the z -axis points upwards and the y -axis is horizontal. If U , V , and W describe the mean flow and u , v , and w are the perturbations from the mean flow along the x -, y -, and z -axes, respectively, and K_j is the kinematic viscosity for each axis j , the governing equations can be expressed as:

$$U \frac{\partial u}{\partial x} + V \frac{\partial u}{\partial y} + W \frac{\partial u}{\partial z} = -\frac{\partial p}{\partial x} + K_x \frac{\partial^2 u}{\partial x^2} + K_y \frac{\partial^2 u}{\partial y^2} + K_z \frac{\partial^2 u}{\partial z^2} \quad (1)$$

$$U \frac{\partial v}{\partial x} + V \frac{\partial v}{\partial y} + W \frac{\partial v}{\partial z} = -\frac{\partial p}{\partial y} + K_x \frac{\partial^2 v}{\partial x^2} + K_y \frac{\partial^2 v}{\partial y^2} + K_z \frac{\partial^2 v}{\partial z^2} \quad (2)$$

$$U \frac{\partial w}{\partial x} + V \frac{\partial w}{\partial y} + W \frac{\partial w}{\partial z} = -\frac{\partial p}{\partial z} + K_x \frac{\partial^2 w}{\partial x^2} + K_y \frac{\partial^2 w}{\partial y^2} + K_z \frac{\partial^2 w}{\partial z^2} \quad (3)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (4)$$

By applying Fourier transform in the in-plane (y - and z -) directions and applying the wave numbers k and m , respectively, the equations can be represented in the Fourier space. For inflow problems, only the outer inviscid solution is solved based on a single boundary condition, i.e. the set of line-of-sight velocities. The out-of-plane (u -) perturbation is iterated until the LINCOM calculated wind fields match the lidar measured radial wind speeds. More information about the derivation of the outer solution is detailed in [6].

Validation Method

The validation of the 3D inflow reconstruction was done in three steps. First, basic generic wind descriptions were used to calculate the projected lidar line-of-sight measurements and used as a boundary condition input for LINCOM. Secondly, a post-processed full-field LES simulation of wind turbine inflow was used to simulate SpinnerLidar measurements and, as such, yield the input for LINCOM. Virtual measurements were performed by the Lidar Scanner Simulator (LiXim) [7] developed at ForWind, Oldenburg. This software enables a simulation of a lidar scanner, also considering kinematics and probe volume averaging. It has to be applied on a post-processed wind field, e.g. generated by a LES. Finally, the model predictions are compared with measurements from a nacelle-mounted SpinnerLidar [8] and the outcome is validated against a virtual met mast created by a 3D short-range WindScanner system.

2.1. Performance with Deterministic Wind Fields

The following deterministic wind field cases were investigated: First, a logarithmic inflow wind profile with a friction velocity of $u_* = 0.5 \text{ m s}^{-1}$ and a roughness length of $z_0 = 0.1 \text{ m}$ is tested, followed by a homogeneous inflow with a horizontal direction offset of 15° . Finally, a radially symmetric, Gaussian flow profile, which could be seen as a rough representation of a wind turbine wake is tested. Each wind field had a low spatial turbulence intensity TI of around 2.5%, defined as Gaussian noise on the calculated line-of-sight speed v_{LOS} . Please note that this is only a rough assumption for realistic atmospheric turbulence.

2.2. Performance with Lidar Simulator (LiXim) Wind Fields

This part of the validation considers a much more complex flow, generated by a LES simulation for neutral stratification and then used together with LiXim to generate line-of-sight measurements as an input to LINCOM. The benefit of this way of validation is the possibility to directly compare the results with the original wind field (see the upper row of plots in Figure 6). The simulation input corresponds to a logarithmic wind profile with a friction velocity of $u_* = 0.5 \text{ m s}^{-1}$ and a roughness length of $z_0 = 0.05 \text{ m}$. The turbulence intensity of the field is approximately 8% at hub height.

2.3. Performance with Full-Field Lidar Measurements

High resolution full-scale measurements of the inflow of a 2.5 MW turbine were performed at the ECN research turbine with SpinnerLidar and short-range WindScanner measurements as part of the IRPWIND joint experiment SCANFLOW [9]. The LINCOM solver is applied to the full 10-minute dataset written as a single input file of high resolution line-of-sight wind speeds measured by a nacelle-mounted SpinnerLidar. The lidar scans a full 2D rosette pattern with 400 line-of-sight wind speed measurements every second parallel to the rotor plane approximately $0.8D$ upstream of the wind turbine.

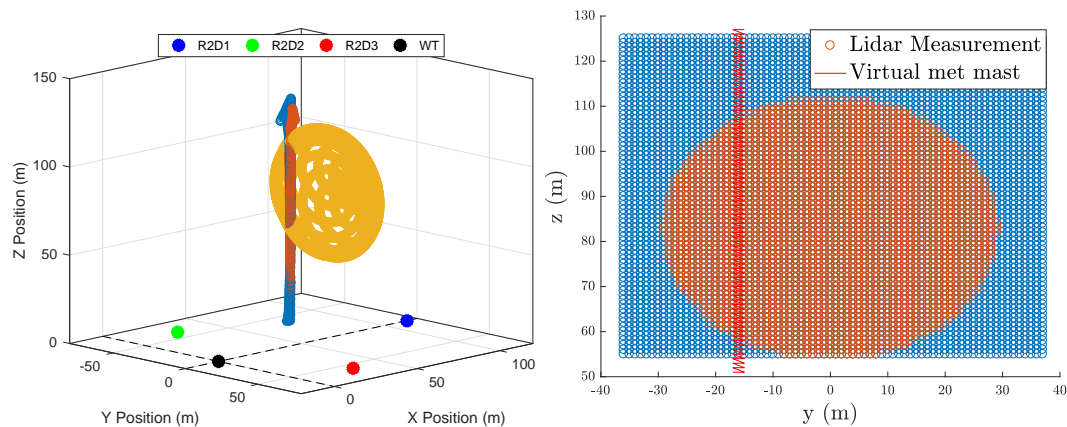


Figure 1. Measurement set-up during the SCANFLOW experiments. Left: The positions of the WindScanners R1D1, R2D2, and R3D3 are shown along with the position of the turbine and the virtual met mast extending from 10-130 m. The SpinnerLidar ‘rosette’ trajectory is marked in orange with the virtual met mast located at $x = 63 \text{ m}$, $y = -22 \text{ m}$; Right: Location of the virtual met mast created from the SpinnerLidar measurement plane.

Figure 1 shows the measurement set-up consisting of the three short-range WindScanners known as R1D1, R2D2, and R3D3, scanning a virtual met mast on the SpinnerLidar measurement plane. For the purpose of analysis, a ten minute dataset was chosen from the

day 29-01-2017 between 11:40 to 11:50. The SpinnerLidar data was filtered based on the gaps in the WindScanner data in order to have the same data availability for both the systems. The mean wind speed and turbulence intensity at hub height, measured by the met mast anemometer, are 8.8 m s^{-1} and 13.1%, respectively. The wind inflow direction is 221° and the mean yaw error of the turbine is calculated to be 1° . The WindScanner measurements are compared with the SpinnerLidar measurements by creating a virtual met mast in the SpinnerLidar measurement plane as seen in Fig. 1 (right) based on the mean yaw position of the turbine and the measurements between the heights 50 m and 110 m are analysed. Now, the ability of the LINCOM model to reconstruct the full scale measurements is tested.

3. Results

The results section is divided into the three different validation parts introduced before.

3.1. Reconstruction of Deterministic Wind Fields

The validation process based on deterministic wind fields was done in the following three steps:

- (i) An analytical wind field description was used to calculate a 3D wind field at a single plane.
- (ii) The wind field was used to calculate the projected lidar line-of-sight wind speeds $v_{LOS} = f(u, v, w)$ in the reference frame of the lidar measurement trajectory.
- (iii) The ‘virtual lidar measurements’ simulated in the previous step are fed into a LINCOM-based wind field reconstruction tool to resolve the three wind speed components again.

The first of three tested deterministic wind fields is the logarithmic inflow wind profile. Figure 2 shows the reconstructed three wind components of this wind field. Note that v and w are defined as the in-plane components and u is the out-of-plane component pointing towards the observer. The total in-plane wind vector $\sqrt{v^2 + w^2}$ is visualised separately as a vector field. It can be seen that the u -component resembles the logarithmic profile input. The v -component mainly fluctuates around zero according to the turbulence. The w -component differs from the input (0 m s^{-1}) in the sense that it shows a virtual upward flow in the middle region, resulting from the LINCOM tool balancing the conservation of mass and momentum.

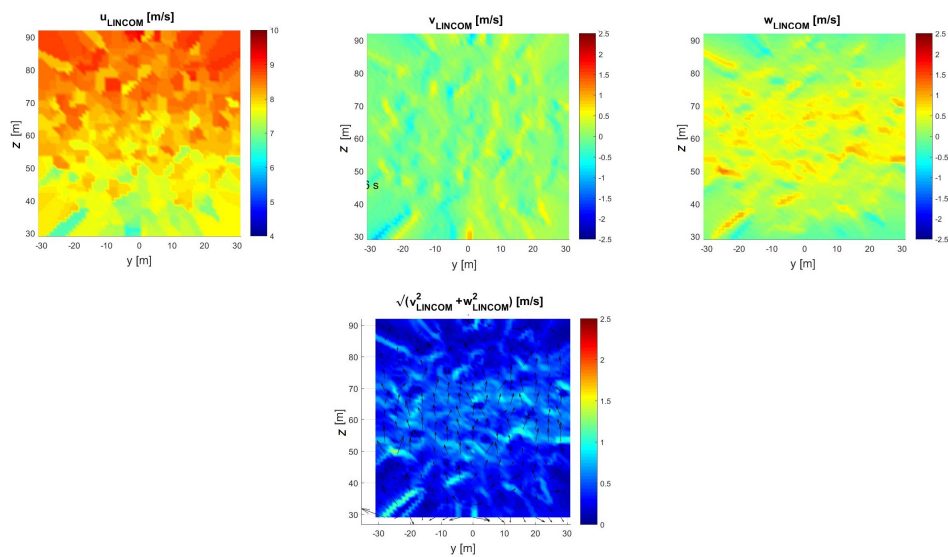


Figure 2. Instantaneous scanned frame of a deterministic inflow wind field with a logarithmic vertical wind shear profile reconstructed by LINCOM from simulated lidar measurements.

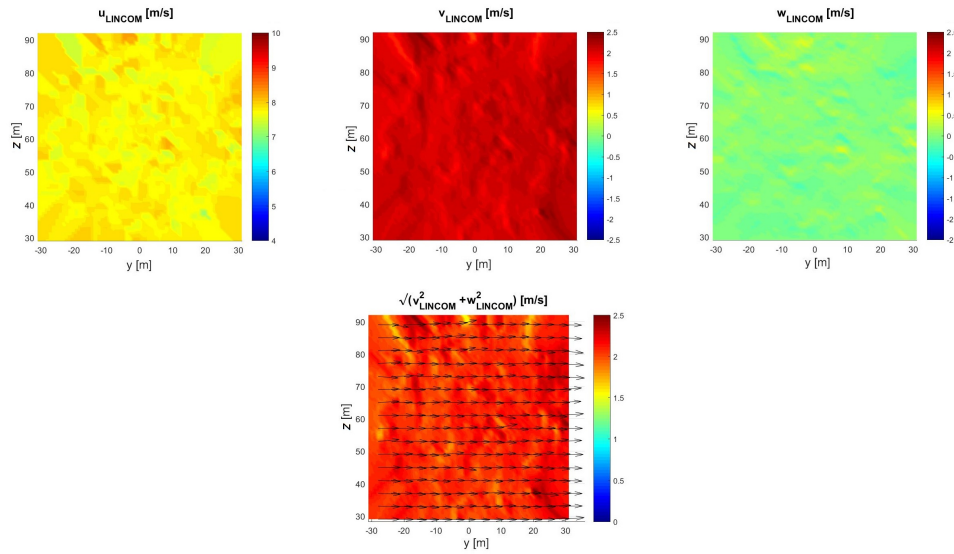


Figure 3. Single frame of a deterministic inflow wind field with a direction offset reconstructed by LINCOM from simulated lidar measurements.

The second deterministic wind field is a homogeneous inflow with a wind speed of 8 m s^{-1} and a wind direction of 15° . Again normally distributed, homogeneous turbulence with $TI = 2.5\%$ was used. In the reconstructed wind field, plotted in Figure 3, the u - and v -components fluctuate around $8 \cdot \cos(15^\circ) = 7.7 \text{ m s}^{-1}$ and $8 \cdot \sin(15^\circ) = 2.1 \text{ m s}^{-1}$, respectively. The vertical w -component resembles its zero definition. The in-plane vector field clearly indicates the wind direction as well. This simple inflow case shows that the LINCOM tool is able to clearly see a misalignment from the lidar line-of-sight measurements.

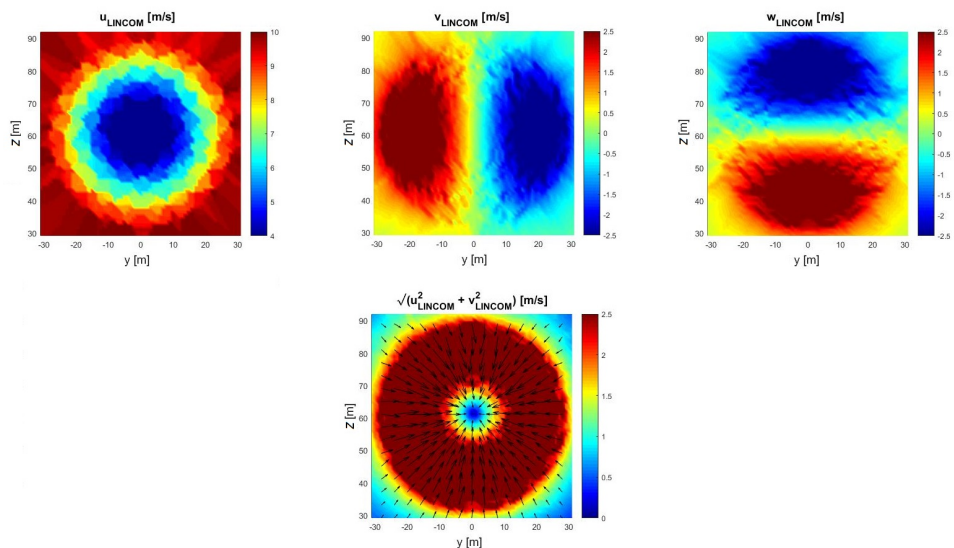


Figure 4. Single frame of a deterministic Gaussian wake deficit reconstructed by LINCOM from simulated lidar measurements.

The third and final deterministic wind field is a simple definition of a Gaussian shaped wake deficit. This was meant to resemble a flow with a free-stream wind speed of about 10 m s^{-1} .

The reconstructed wind field components are plotted in Figure 4. By only determining the out-of-plane u -component, the flow would undermine the conservation of mass and momentum equations and thus LINCOM converges to a solution where the radially symmetric in-plane flow is pointing radially inward with wind speeds over 2.5 m s^{-1} .

3.2. Turbulence Study on Deterministic Wind Fields

For the first case shown in the previous subsection, i.e. the basic logarithmic profile (see Figure 2), a sensitivity study on turbulence intensity was executed. For turbulence intensities between 0% to 10% on the u -component, a total of 60 wind fields are generated with normally distributed homogeneous turbulence. The lidar is simulated and LINCOM is used to reconstruct the wind fields. Considered here are the root mean square error (RMSE) and the goodness of fit coefficient (R^2) based on all points on the wind field over the 60 different cases. The resulting dependencies are plotted in Fig. 5. It can be seen that the error for the laminar case is minimal and the model works quite well for cases with very low turbulence. Please note that the error in w is offset, because the definition of both v and w being zero over the wind field, is not a realistic solution to the conservation of mass and momentum equations, so LINCOM reconstructs a nonzero w -component (see Figure 2). For cases above 5% turbulence intensity, the RMSE seems to get an almost linear dependency on the TI and LINCOM creates relatively large errors on the reconstructed wind field. The R^2 values are only acceptable ($R^2 > 0.5$) until ca. 3% turbulence. This leads to a conclusion that the model only works sufficiently for low turbulent conditions.

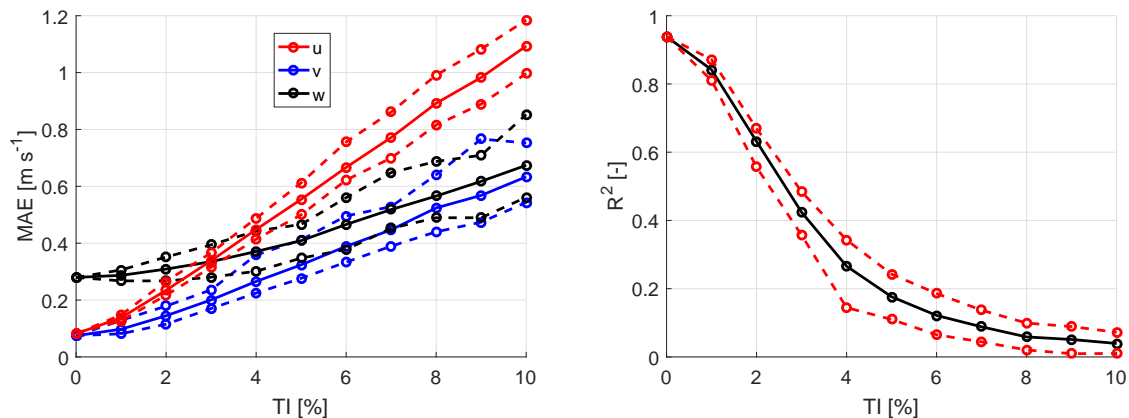


Figure 5. Sensitivity study of the reconstructed logarithmic profile wind field for turbulence intensities ranging between 0% to 10% Left: RMSE; Right: Goodness of fit coefficient R^2 .

3.3. Reconstruction of Lidar Simulator (LiXim) Wind Fields

To test the capability of the LINCOM tool to reconstruct more complex wind fields than the deterministic ones, it was applied on a one-minute time series of LES inflow. Lidar measurements were simulated using LiXim [7] to extract the line-of-sight measurements from the LES volume. The lidar measurements were formatted to the LINCOM input format and used to reconstruct the wind field again. Figure 6 shows the comparison between the reconstructed wind field and the original simulation. On a first impression, it seems that the u -component is reconstructed successfully, contrary to the other two components. The latter indicate structures that were not present in the original LES simulation.

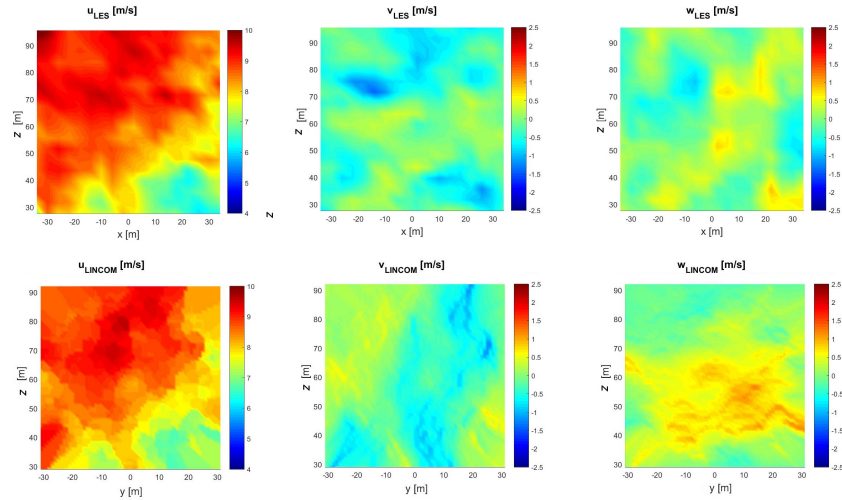


Figure 6. Single frame of a LES simulated inflow wind field reconstructed by LINCOM from simulated lidar measurements.

To compare the reconstruction to the original wind field in a statistical way, a correlation of all u -components across the wind field over the entire one-minute duration was done. In Figure 7 two regression curves are depicted, the left one correlating the u -components reconstructed by LINCOM with the original LES components, and the right one correlating the de-projected lidar measurements with the original LES. This de-projection assumes that all components other than u are zero and defines this component by projecting the line-of-sight measurement into the u -direction by only considering the azimuth angle χ and the elevation angle δ of the laser beam (see Eq. 5).

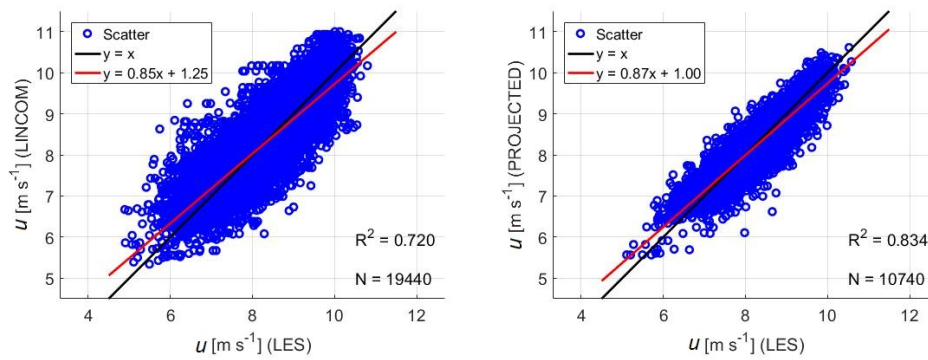


Figure 7. Comparison of the correlation of a minute of reconstructed wind flow. Left: LINCOM based reconstruction; Right: Simple one-dimensional de-projection on the u flow component.

$$u_{projected} = \frac{v_{LOS}}{\cos(\chi) \cos(\delta)} \quad (5)$$

Contrary to the expectation, the de-projected wind speed shows a higher goodness of fit coefficient ($R^2 = 0.834$) than the LINCOM reconstruction ($R^2 = 0.720$). This is probably due to the difficulty of reconstructing the v - and w -components with sufficient accuracy. No significant correlation exist between the reconstruction and the original LES for those in-plane components.

3.4. Reconstruction of Full-Field Lidar Measurements

The u -, v - and w - components, which are calculated by the LINCOM model by fitting them to the v_{LOS} measurements, are validated with the measurements from three synchronised short-range WindScanners performing a virtual met mast on the SpinnerLidar measurement plane performed during the SCANFLOW campaign as seen in Figure 1. Figure 8 shows the extracted instantaneous u -, v -, and w -velocities from the SpinnerLidar line-of-sight measurements. It should be noted that the velocities are denoted in the turbine frame of reference (see Fig. 1).

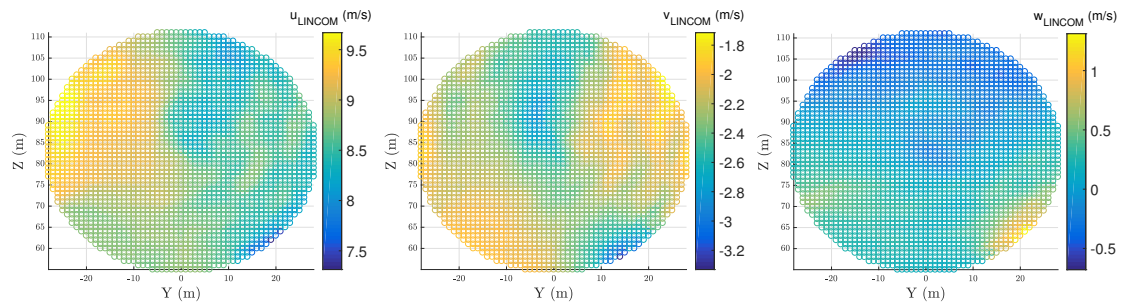


Figure 8. Instantaneous u -, v -, and w -components obtained from the SpinnerLidar v_{LOS} measurements at $t = 1$ s.

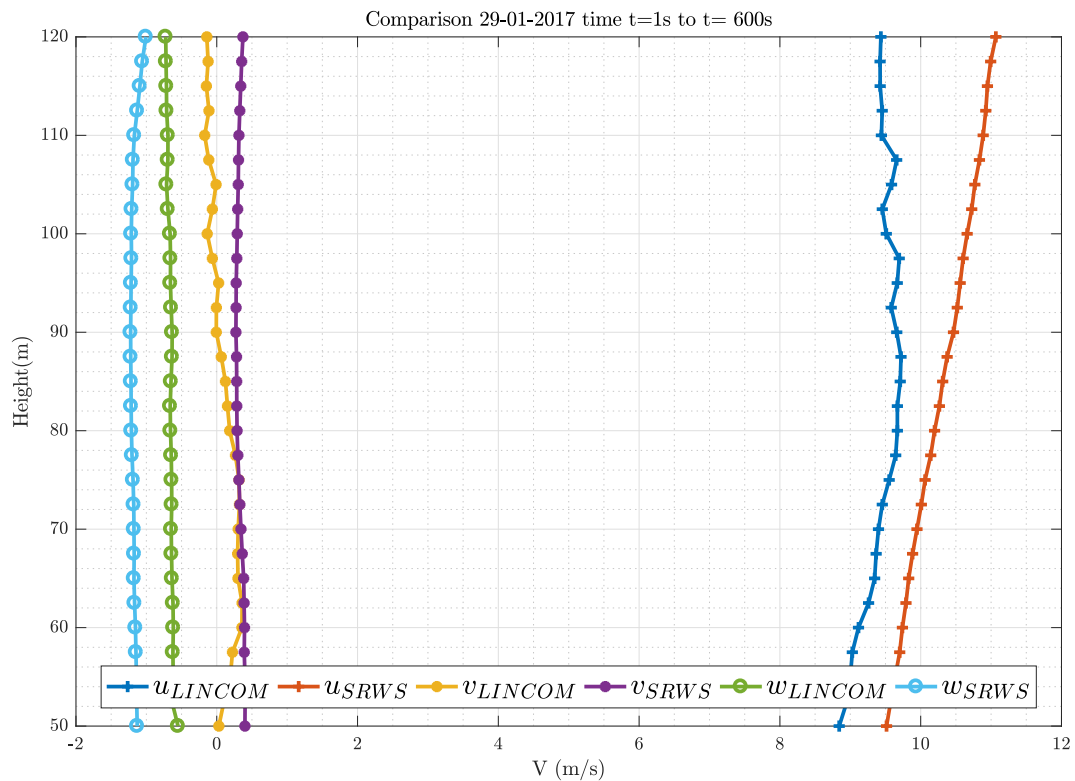


Figure 9. Comparison of the virtual met mast measurements obtained from the LINCOM model and the WindScanner for the 10-minute dataset.

The comparison between the virtual met mast measurements obtained for the LINCOM model applied to the SpinnerLidar measurements and the measurements of the WindScanner

averaged for the entire 10-minute data set is displayed in Fig. 9. The wind speeds calculated by the LINCOM model follow the wind speeds measured by the WindScanners with differences in magnitude depending on the chosen averaging interval. It can be seen that the longitudinal u -component obtained from the LINCOM model is lower than the WindScanner measurements by 0.8 - 1.2 m s⁻¹. The lateral v -component obtained by the LINCOM model is over-predicted when compared to the WindScanner measurements by 0.5 m s⁻¹. The reconstruction of the vertical w -component matches the WindScanner measurements with a mean difference of 0.2 m s⁻¹. A possible reason for the difference in the u - and v -components is the highly turbulent wind inflow.

For statistical analysis of the LINCOM reconstruction, an error term V_{error} is introduced in order to calculate the error associated with the different averaging intervals of the LINCOM measured wind fields which can be defined as:

$$V_{error} = \frac{V_{LINCOM} - V_{WindScanner}}{V_{WindScanner}} \quad (6)$$

Here, the measurements from the WindScanner are considered as reference measurements. For the purpose of real-time turbine control, it is important to know the relative error between the LINCOM calculated velocities and the WindScanner measurements representative of the real wind speeds for different averaging intervals. Table 1 shows the relative error for different averaging intervals from one second to one minute. The relative error for the u -component is around 15% for shorter averaging intervals for less than 20 seconds. The v - and w -components have a standard error of 65% and -63%, respectively for short averaging intervals. The high standard error values for v and w can be explained by the small velocity magnitudes for these two components. The relative error for the 1 Hz measurements shows a large deviation from the others, because the measurements points of the SpinnerLidar and the WindScanner are not synchronised at high sampling rates. For correlated variables, it is expected that the relative error decreases with respect to the sampling interval. Since this is not the case, we conclude that there is no sufficient correlation between the WindScanner measurements and the LINCOM output for this case. The turbulence intensity of 13.1% is probably too high for an accurate wind field reconstruction, which is another confirmation of the shape of the R^2 plot in Fig. 5.

Table 1. Relative error calculated for different averaging intervals.

Interval (s)	$u_{error}(\%)$	$v_{error}(\%)$	$w_{error}(\%)$
1	-13.4	65.2	-73.0
5	15.5	65.2	-65.1
10	15.5	67.1	-63.8
15	17.4	56.8	-50.5
20	16.9	67.1	-39.2
30	22.1	71	48.1
45	23.4	78	51.2
60	19	82	66.7

4. Conclusions and Outlook

The LINCOM wind field reconstruction methodology is a tool that can be used to reconstruct the main features of wind fields from non-aligned v_{LOS} measurements recorded by a SpinnerLidar. The capabilities of the current LINCOM model to reconstruct the three velocity component from the line-of-sight measurements have been evaluated ranging from simple deterministic wind fields, LES simulations and finally full-scale boundary layer experiments. The results suggest

the general suitability of the LINCOM model to reconstruct the stationary features of 3D wind fields under certain conditions, such as non-rotational flows.

It has been showed that the LINCOM reconstruction methodology is capable of reconstructing the deterministic wind fields with low turbulence with appropriate accuracy. The RMSE error for all three components increases more or less linearly with increasing turbulence. The performance of the model for the LES test case yielded a goodness of fit coefficient $R^2 = 0.72$ for the longitudinal component with no significant correlations existing for the lateral and the vertical components. A simple projection of the line-of-sight to the x -direction yielded a better coefficient, i.e. $R^2 = 0.834$. Although the v - and w - components cannot be calculated precisely, the main flow features and their mean values are sufficiently accurate and provide valuable information about the wind field that cannot be seen from solely the lidar line-of-sight measurements. For the full field measurements, the LINCOM reconstruction method was able to reconstruct the three wind field components with errors of 15%, 65% and -63%, respectively, for a averaging period of 10 s. These errors can be attributed to the high turbulence intensity of 13.1%. The high percentage error of the crosswind components is caused by the relatively low absolute values of the v - and w -components. It can be concluded that the LINCOM model is able to accurately reconstruct the along-wind component under certain conditions. The model is able to provide a reasonable approximation only for the mean of the cross-wind components.

Further research is necessary, and will be focused on developing the LINCOM reconstruction model and analysis of the model under high turbulence conditions and the implementation of boundary conditions for the inner solution in order to accurately calculate the cross-wind components. Furthermore, the model will be further developed and tested for different inflow and wake cases obtained from full-scale measurements.

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